Diversity within Geodiversity, Underpinning Habitats in New South Wales Volcanic Areas

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New South Wales National Parks, Nature Reserves, State Conservation Areas and other reserves lie in diverse geological settings. One component, Cenozoic volcanic rocks, includes eroded basaltic fields, some representing shield volcanoes with central cores of silicic rocks. The central shields provide diverse habitats in the Tweed-Main Range, Nandewar, Ebor-Dorrigo, Warrumbungle and Canobolas areas. These shields result from deep geodynamic causes and increase in age, size and degree of erosion northwards giving systematic habitat variations. The northern Tweed structure (23–25 mya) exhibits lava aprons, erosional caldera rims, basement valley floors and an isolated central intrusive peak, whereas the southern Canobolas structure (11–13 mya) retains a general shield profile. Some basaltic fields had prolonged eruptive histories, as in Barrington Tops NP (60–4 mya). There, lavas form an incised plateau rimmed by valleys and escarpments. Similar lava fields occur in other parks and reserves, e.g. Mummel Gulf NP and Ben Hall Gap NP, but fertile basalt soils mostly promoted agricultural/forestry use. A marine park at Lord Howe Island lies on a submarine plateau cut into a 7 mya basaltic volcano. The volcanic landscapes provide scenic recreational parks and platforms for habitat studies, aboriginal history, geo-education and geo-tourism.

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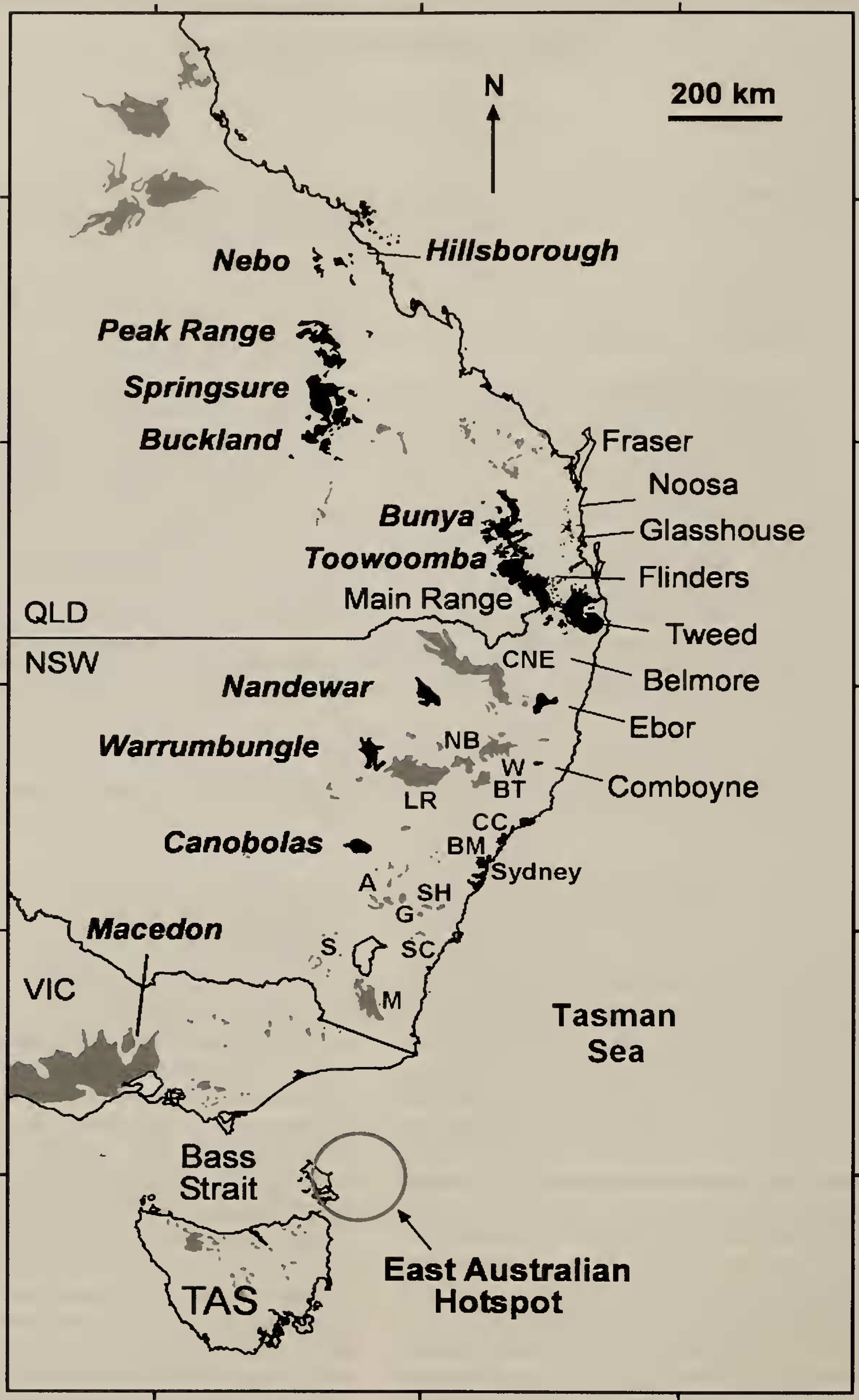
KEYWORDS: basalt fields, central volcanoes, geodiversity, habitats, Lord Howe Island, National Parks, New South Wales.

INTRODUCTION

New South Wales encompasses diverse geological settings related to different times within an extended geological history from Precambrian to Recent. The different units have been subjected to a range of erosional events since the break-up of eastern Gondwana (Scheibner 1999; Branagan and Packham 2000; Veevers 2001). One component that plays a prominent role within many National Parks, forestry and conservation reserves is Cenozoic volcanic rocks. This stems from their relatively widespread distribution, particularly in eastern NSW, and contrasting erosional forms and soil development given by silicic and basaltic lithologies within them (Sutherland 1995). This NSW component is part of a more extended array of such rocks along eastern Australia (Fig.1), which also includes seamounts and island chains along the Tasman and Coral Seafloors (Vasconcelos et al. 2008). This paper aims to summarise this volcanic component in NSW where it underpins a range of habitats in National Parks (NP), State Conservation Areas (SCA), Nature Reserves (NR), Marine Parks (MP), Forestry Reserves (FR) and Aquatic Reserves (AR). Among c. 570 landscape types identified in NSW, two thirds are found in these reserves (Mitchell 2003). Photographic images will illustrate a range of these landforms and habitats that exist within their precincts. It is hoped that this survey will stimulate more detailed biological studies within these linked habitats and allow further assessments of these areas for geo-heritage values, potential geo-education themes and geo-tourist activities.

Brief descriptions of these volcanic features within the main NSW parks and preservation areas (Explore Australia Publishing 2010) incorporate new dating on the rocks and some unpublished data. Updated information on the national parks, reserves, conservation areas and forestry reserves can be accessed on a range of websites, e.g. www.bigvolcano.com.au/; www.environment.nsw.gov.au/; www.nationalparks.nsw.gov.au/. A progress report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East Australian
Hotspot

lists geoheritage values for some of the volcanic holdings (Osborne et al. 1998).

GEOLOGICAL SETTING

The Late Cretaceous-Cenozoic volcanism that created the range of remnant land forms now exposed in New South Wales was similar to that now seen in active volcanoes observed in other within-plate basaltic areas such as the Hawaiian Islands. Volcanic activity would have ranged from relatively calm effusions and lava fountaining, through more continuous gas blasting of larger ejected blocks and in some cases more extreme explosive activity forming towering Plinian-style eruptive columns (Parfitt and Wilson 1995, 1999). Lava flows ranged from blocky to ropy forms that could encase internal drainages of lava and extend into long lava flows (Cashman et al. 1998; Sheth 2003). As in Hawaii, some of the volcanoes developed large shields over deep magma chambers (Kauhikau et al. 2000) from which more evolved silicic rocks could rise into their summits (Bohrson and Reid 1997; Van der Zander et al. 2010). Such volcanos are called central volcanoes in eastern Australia and the Tasman Sea; in similar fashion to their Hawaiian and other counterparts they show a progressive increase in age away from a deep fixed mantle 'hot spot', as the overlying plate moved across the melting zone (Duncan and McDougall 1989; Vasconcelos et al. 2008). These linear chains of central volcanoes show some gaps and bends in their paths, which are related to further deep geodynamic processes or crustal collisions (Sutherland 2003; Knessel et al. 2008). In inland NSW, several minor volcanoes formed of a potassic lava leucitite also formed a linear age chain related to Australia's northward movement (Cohen et al. 2008). These leucitite volcanoes do not include significant parks or reserves and are not considered further in this paper. The majority of volcanoes in eastern Australia are basalt-only lava fields. These volcanoes are less clearly related to Australia's northward plate motion and were erupted in sporadic bursts from c. 100 mya to near-recent times.

Figure 1. LEFT, Eastern Australia, showing relationships of NSW volcanic fields to the overall Cenozoic volcanic distribution. Central volcano fields (black areas) are named as major centres (inland, bold italics; coastal. non-italics) and are shown in relation to a present East Australian hotspot position. Basalt fields (grey areas) are designated in NSW by symbols for the main fields described in this study (CNE Central New England; NB North Barrington; W Walcha; LR Liverpool Range; BT Barrington Tops; CC Central coast; BM Blue Mountains; A Abercrombie, SH Southern Highlands; S Snowy ; M Monaro). The diagram is adapted from Cohen et al. (2008).

The main New South Wales volcanic fields discussed in this paper show differences in age distribution between the central volcanoes and basalt lava fields (Fig. 2). General ages of basalt lava fields and central volcanoes in NSW based on K-Ar dating and the relationship of the central volcano trend to past plate motions of eastern Australian from 90 mya to the present are depicted in Fig. 3. Where more reliable dating of the rocks is available using the $^{40}Ar/^{39}Ar$ method (Cohen 2007), it is designated as Ar-Ar dating in this account. The contrast in the compositional ranges for typical rock types found in central and basaltic lava field sequences is illustrated using two examples from northern NSW (Table 1).

CENTRAL VOLCANO COMPONENT

Tweed Volcano

This is the largest central shield (80 x 100 km across) and straddles the NSW-Qld border region (Duggan et al. 1993). Its growth is now dated as at least 24.3 ± 0.4 to 23.1 ± 0.2 mya (Ar-Ar dating; Knessel et al. 2008), although the full stratigraphical range of lavas from Tweed remains to be analysed (B. E. Cohen, pers. comm. 2010). Progressive erosion of the original structure (Willmott 2003, 2010) has reduced its landscape to (1) remnant basaltic lava aprons on its northern, western and southern sides, (2) escarpments where an 'erosional' caldera occupies the valley floors of the Tweed River systems (Fig. 4a) and (3) a prominent isolated central peak (Mount Warning), with some surrounding ring dyke protrusions, left by the more resistant intrusive conduit of the volcano (Fig. 4b). The highest remnant lies at 1175 m asl and the flows extend to below sea level. Tomewin Rock on the NSW border is a coarse rhyolite agglomerate that seems to represent an initial violent phase of the Tweed Volcano (Willmott 2010).The basaltic apron does not extend south into the Alstonville-Ballina area where older (27–41 mya) flows are exposed (K-Ar dating; Cotter 1998). The Border Ranges NP, Wollumbin NP (including Mount Warning NP), Mebbin NP, Nightcap NP, Whian Whian SCA and Cook Island AR are areas where views of remnant rocks of the Tweed volcano are encountered. Mount Warning is also named 'Wollumbin' an aboriginal

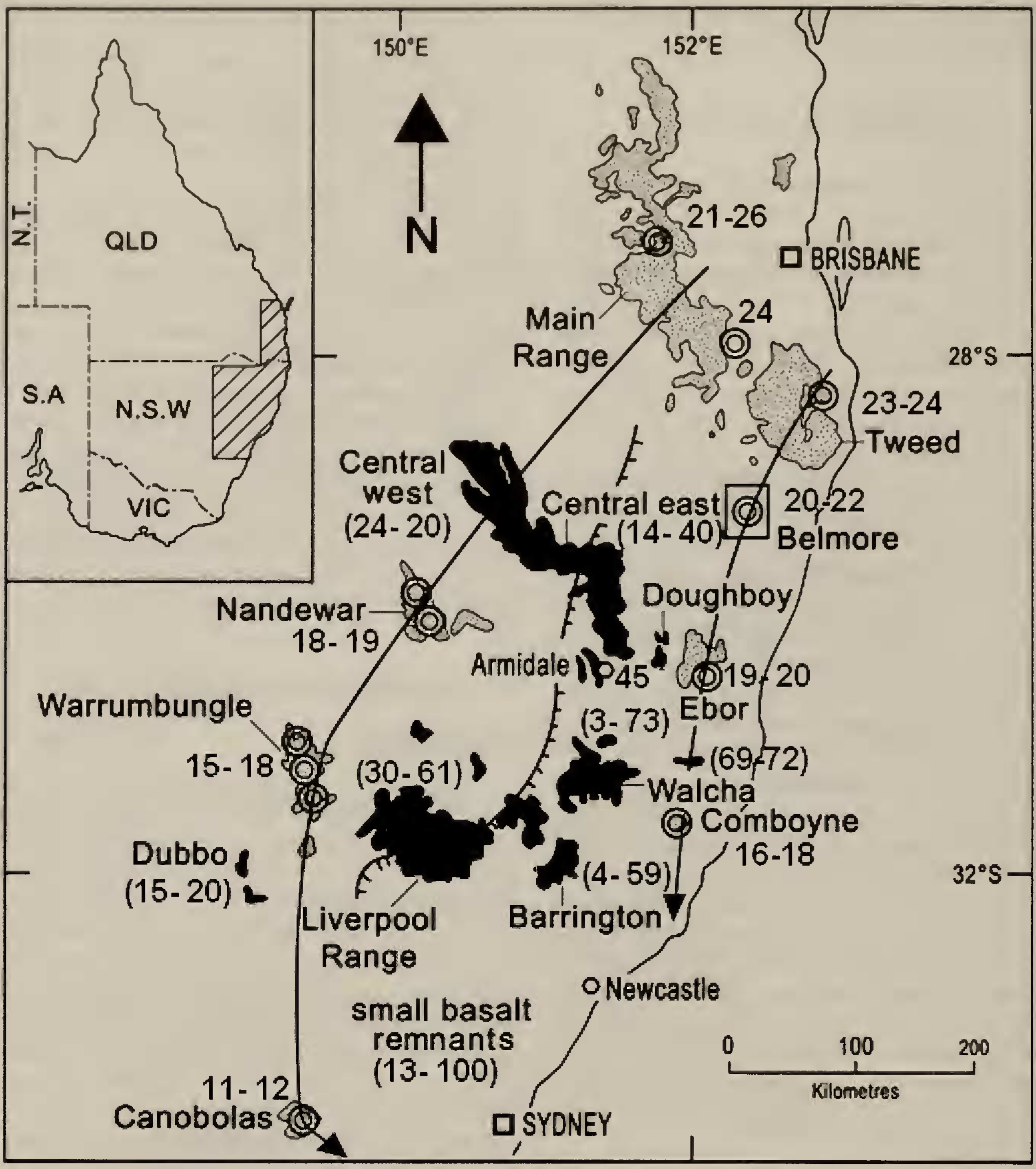

Figure 2. Distribution of central volcanoes (stippled areas) and basalt lava fields (black areas), Qld-NSW (26–34°S), showing ages in mya (Ar-Ar ages, no brackets; K-Ar ages, brackets), general central volcano progressive age trends (arrowed lines) and western edge of the Sydney Basin (hatched line). The Belmore central volcano is outlined by a box to indicate its unusual silicic nature. The diagram is modified from Sutherland et al. (2005b).

name for a fighting chief, although some applications of aboriginal place names and history in the area are controversial. One elder source maintains the peak and adjacent caldera was known as 'Walambing Momoli' by the Ngarakwal people, which described its silhouette as a scrub turkey and its nest (Boileau 2006).

Many of the parks and reserves within this volcanic apron form part of the Gondwana Rainforests of Australia World Heritage Site (UNESCO 2010). The geology, characteristic land forms, typical soils and vegetation regimes of these areas are listed for the North Coast subregions (www.environment.nsw.gov.au). The Border Ranges NP, because of its many

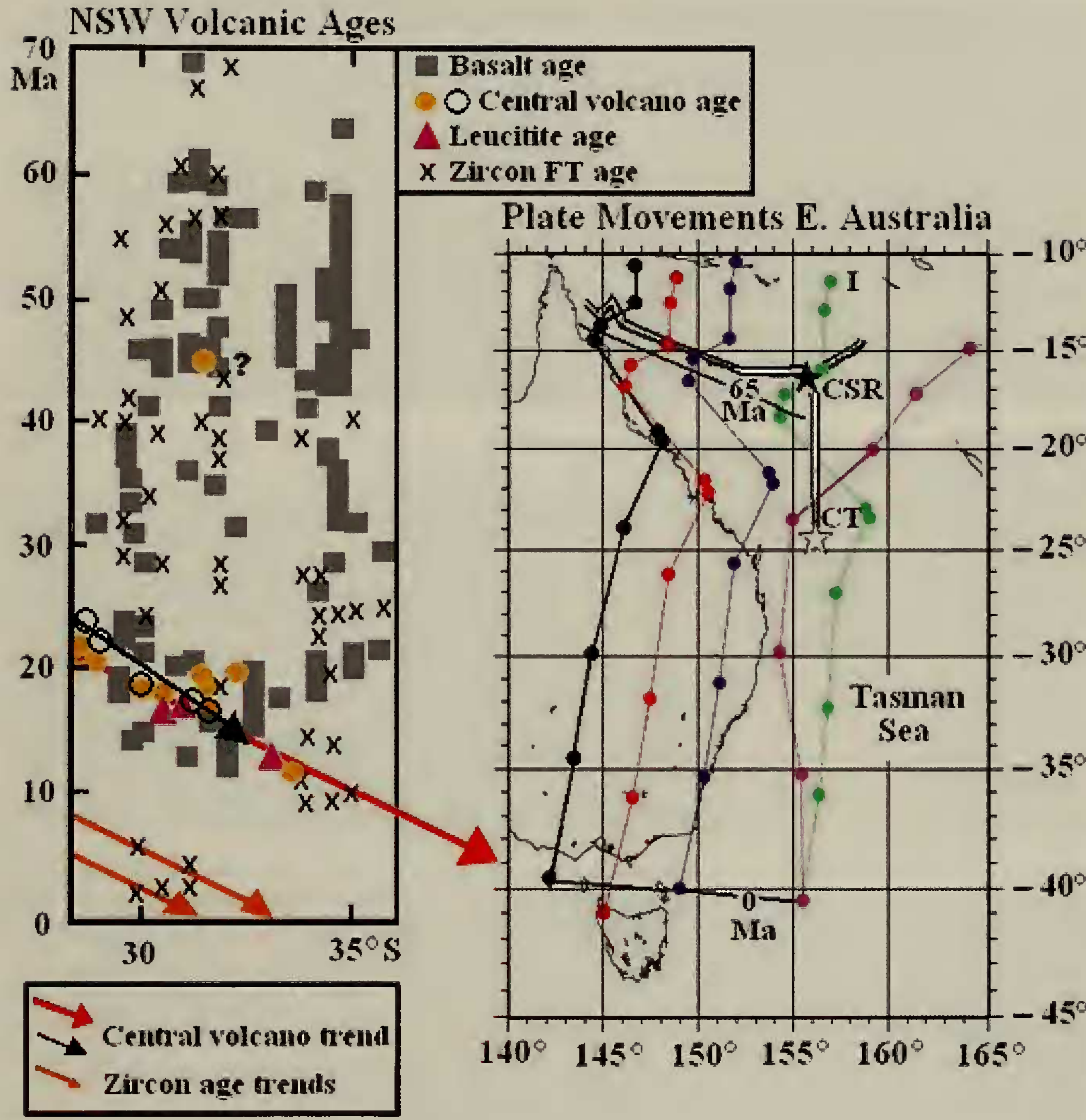

Figure 3. Left side: Age (K-Ar)-Latitude plots for NSW basaltic fields (filled spaces), central volcanoes (filled circles), leucitite fields (filled triangles), zircon fission track eruptive reset ages (crosses) and progressive age trends (arrows). The diagram is adapted from Sutherland (2003). Note that the Central volcano trend (arrow) would differ slightly in position using Ar-Ar dating (open circles trend). The central volcano age trend (arrow head) is related to a present East Australian plume line positions at 0 mya (0 Ma line), shown in the right hand side map. Right side: Plate movement map showing past plume line positions (coloured circles with tracks) reconstructed at increasing 10 mya intervals northwards from 0–90 mya. The past positions are based on an Indian-Atlantic Ocean hotspot reference frame (I); one track (purple circles) is based on a Pacific hotspot reference frame for comparison (Maria Seton, University of Sydney, plate movement program). The Coral Sea Ridge (CSR) and Cato Trough (CT) spreading ridge system (double line) and triple point positions (stars) are shown relative to a 65 mya position

Table 1. Comparative compositional ranges for some NSW volcanic fields Compositional ranges are summarised from cited literature and earlier listed references

Rock Type	SiO_2	Al_2O_3	Total FeO	MgO	Na_2O	K_2O
Tweed-Focal Peak central volcano sequence (significant silicic component)						
Basanite suite	44.5–46.8	14.7–15.1	12.4–11.3	8.7–9.0	3.6–3.8	0.8–1.5
Alkali basalt suite	45.6–47.5	13.5–16.3	10.8–13.3	4.5–10.2	3.0–4.7	0.7–2.0
Transitional basalt suite	47.9–48.1	15.6–16.9	9.0–12.2	4.7–4.9	3.9–4.1	1.5–1.6
Tholeiitic basalt suite	50.6–55.7	14.4–15.4	8.9–12.9	2.4–8.1	3.3–4.2	0.5–3.6
Silicic suite	58.5–74.3	11.3–15.0	2.3–11.0	0.1–2.8	2.7–5.8	1.9–4.8
Liverpool Range basalt field sequence						
Alkali basalt suite	45.6–47.7	14.9–16.1	9.9–10.2	10.3–11.2	3.0–3.2	1.5–1.8
Tholeiitic basalt suite	47.0–47.6	14.8–15.3	9.9–11.3	9.6–11.1	2.2–2.4	0.9–1.5

distinct landscape habitats in a relatively small area, has the highest concentrations of marsupial species and among the highest concentrations of bird, reptile, amphibian and bat species in Australia. It has particular interest in representing a transition between northern tropical and southern temperate faunal regions. The Lost Wilderness FR within the area includes over 60 threatened plant species. Nightcap NP with its eroded basalt and rhyolite landscape includes significant faunas such as the little-bent winged bat, woompoo fruit dove, masked owl, Stephens banded snake and red legged pademelon, while Whian Whian SCA within the park protects quoll, koala and platypus habitats. Cook Island AR incorporates a basalt pedestal as an important breeding ground for migratory birds and protects surrounding off shore marine reef communities.

Main Range-Focal Peak Volcanoes

This extended volcanic complex (80 x 80 km) west of Tweed volcano is largely exposed in Qld where the youngest basalt cap lies at 1156m asl (Stevens and Willmott 1996, 1998), but its most southern basaltic and silicic parts overlap into NSW (Thompson 1974). The Focal Peak volcano is overlapped by the Tweed lavas but rhyolite plugs assigned to it extend south to Nimbin (Willmott 2010) The Ar-Ar ages for the Qld sector range from 26.4 ± 0.4 to 20.7 ± 0.5 mya, which suggests a wider age span than for the Tweed volcano, but the NSW exposures remain undated. The Nimbin Rocks are rhyolite peaks that mark a sacred aboriginal site named after 'Nyimbunji', a ruler of supernatural powers (Tacon 1998).

The Border Ranges NP includes basalt lavas and some rhyolite plugs, such as Mount Glenie, erupted from the Focal Peak Volcano. Toonumbar NP, Richmond Range NP and Mallanganee NP extend across the more southern eroded remnants of the Focal Peak centre. Toonumbar NP, with peaks such as Dome Mountain, contains World Heritage listed rainforests, where unlogged tree species have been compared with those in surrounding logged areas (Kariuki et al. 2006). The habitats provide protection for threatened animals such as the sooty owl, red-legged pademelon and yellow-tailed glider. Richmond Range NP, which incorporates peripheral basalt flows from Focal Peak Volcano, includes the World Heritage listed Cambridge Plateau and holds an astounding diversity of flora and fauna, with many rare and endangered species. The Koreelah NP, Mount Clunie NP, Tooloom NP and Toobin NP lie within the less investigated NSW volcanic remnants to the west. Tooloom NP follows basalt ridges, includes the World Heritage listed Tooloom Scrub, and is a critical haven

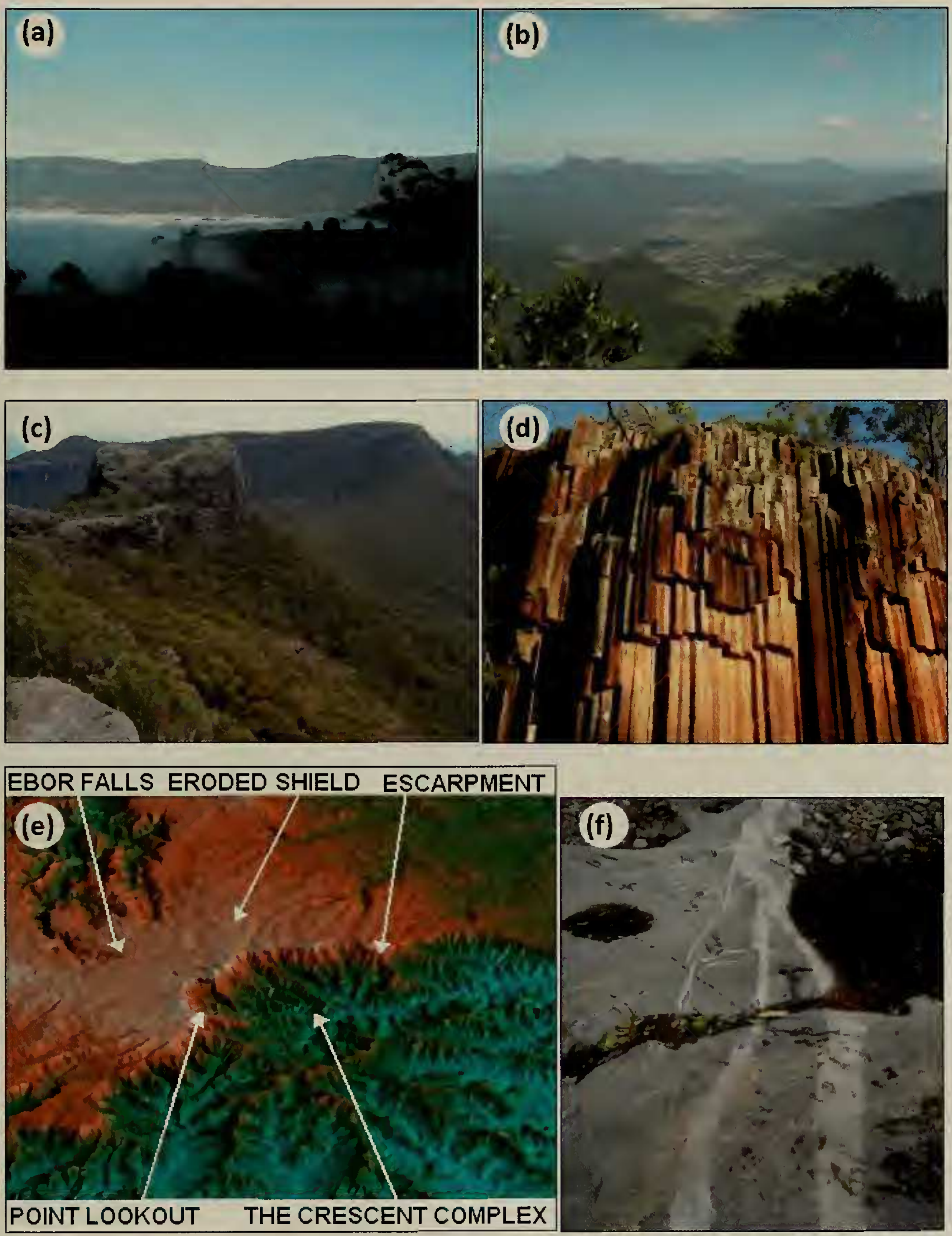

Figure 4. Erosional features developed on older central volcanoes. (a) Border Ranges escarpment, Tweed Volcano. (b) The Mount Warning intrusive complex, from south western lava apron. (c) Governor Bluff, Nandewar Volcano. (d) Sawn Rocks (with columnar jointing), Nandewar Volcano. (e) High altitude perspective of Ebor Volcano partially eroded on the eastern side, forming escarpment (modified from Cohen 2007). (f) Silicic dykes (light coloured) of the Ebor Crescent Complex. Photos: Benjamin Cohen.

for a wide range of threatened wallaby, potoroo, bettong, owl and lyrebird species.

Belmore Volcano

This small central volcano (15 x 20 km), north east of the Clarence River and east of the escarpment, is predominantly silicic in nature without significant remnants of a main basaltic apron (Sutherland et al. 2005b). The lack of basalts is unlikely to represent an erosional event, as only one basalt dyke (post-silicic) was found in the eroded interior. Three silicic rocks are dated at 20.8 ± 0.8 to 21.2 ± 0.3 mya (Ar-Ar dating; Knessel et al. 2008). The highest summit lies at 516 m asl and the lowest remnants lie at c. 200 m asl. Mount Neville NR (www.environment.nsw.gov.au) overlaps an outlying flow ridge from a peripheral vent of the volcano and protects plants such as spike-rush and cabbage tree species at the limits of their geographic ranges.

Nandewar Volcano

This central volcano (30 x 50 km) is exposed in the Mount Kapatur NP (Dawson et al. 2004) and has received detailed petrologic investigations and comment (Duggan et al. 1993; Nekvasil et al. 2004). Limited Ar-Ar dating gives ages of c. 18.5–19.0 mya for the main complex (Cohen et al. 2008). In contrast to the Tweed volcano, much of the central silicic eruptive super structure remains, reaching 1510 m asl (Fig. 3c,d), although the shield is partly dissected by radial drainage which descends through the basalt lavas at plains level (Bob and Nancy's Geotourism site, 2010). The volcanic landforms include outstanding examples of tiered lava terraces, such as Lindsay Rocks, a spectacular set of circular dykes at Mount Yalludundida and a superb example of cooling joints in silicic lava at Sawn Rocks (3d).

Mount Kapatur NP is foremost among Australian conservation areas for the range of vegetation climes that ascend its volcanic slopes over such a short distance. The varied habitats protect a diverse range of plant communities and threatened species of bats, birds, wallabies, quolls and a unique pink slug. The preserved biological communities exhibit both western slopes and tableland affinities within the area and overlaps between both northern and southern species distributions.

Ebor-Dorrigo Volcano

This volcano (40 x 60 km) straddles the present escarpment, producing striking topographic differences across its eroded structure from its high point at 1562 m (Fig. 3e). The volcano formed between 19–20 mya (Ar-Ar dating; Ashley et al. 1995; Knessel et al. 2008). Only the western and northern basaltic aprons show substantial preservation, leaving a decapitated intrusive complex in its eroded centre (Fig. 3f) and a few residual lava caps to the south. A basalt cap at Andersons Sugarloaf (c. 850 m asl), 35 km south of the intrusive core is probably a remnant lava flow from the volcano as it is geochemically similar to analysed Ebor basalts (F.L.Sutherland and I.T. Graham, unpublished analyses). This prominent peak marked a sacred aboriginal initiation site (Kempsey Heritage Inventory; www.kempsey.nsw.gov.au).

The New England NP encompasses volcanic relicts left by escarpment retreat under erosion by the developing Bellingen, Nambucca and Macleay river systems. Guy Fawkes NP includes the west flowing plateau drainage, now entrenched in the basalt apron at Ebor Falls. Dorrigo NP includes some of the basalt apron on its northeastern side and with New England NP they form part of the World-Heritage listed Gondwana Forests of Australia designed to protect stands of Antarctic Beech. The rich basalt soils and wet climate support an exceptional biodiversity. Snow gum woodland, forest and heath on the high plateau pass into towering eucalypt forests and lush rainforest on the slopes.

Warrumbungle Volcano

A central intrusive complex features in this volcano (50 x 80 km), where erosion has exposed spectacular examples of flows, dykes, plugs and domes (Fig. 5 a, b). These showcase a wide spectrum of alkaline rocks (Duggan and Knutson 1993; Duggan et al. 1993; Ghorbani, 1999, 2003). Several Ar-Ar dates indicate that the structure developed from 18 to 15 mya (Cohen et al. 2008). Studies of minerals in the rocks reveal a complex evolution of subsilicic to silicic lavas tapped from deeper mantle and higher crustal chambers (Duggan 1990; Ghorbani and Middlemost 2000). The capping flows reach a high point at 1206 m asl and the eroded intrusive complex is readily accessible in Warrumbungle NP (Whitehead 2009). Peripheral basalt flows mark former radial drainages and descend onto the surrounding plains. "Warrumbungle' is the name given to these peaks by the Gilmaroi aboriginal people, meaning 'crooked mountains'.

Warrumbungle NP, although containing similar volcanic rocks and features to Kaputar NP, shows subtle differences in its landforms and biodiversity to its northern counterpart. The complex incisions within the volcanic edifice produce many diverse microclimates and habitats. Marsupial species abound and include the threatened brush-tailed wallaby,

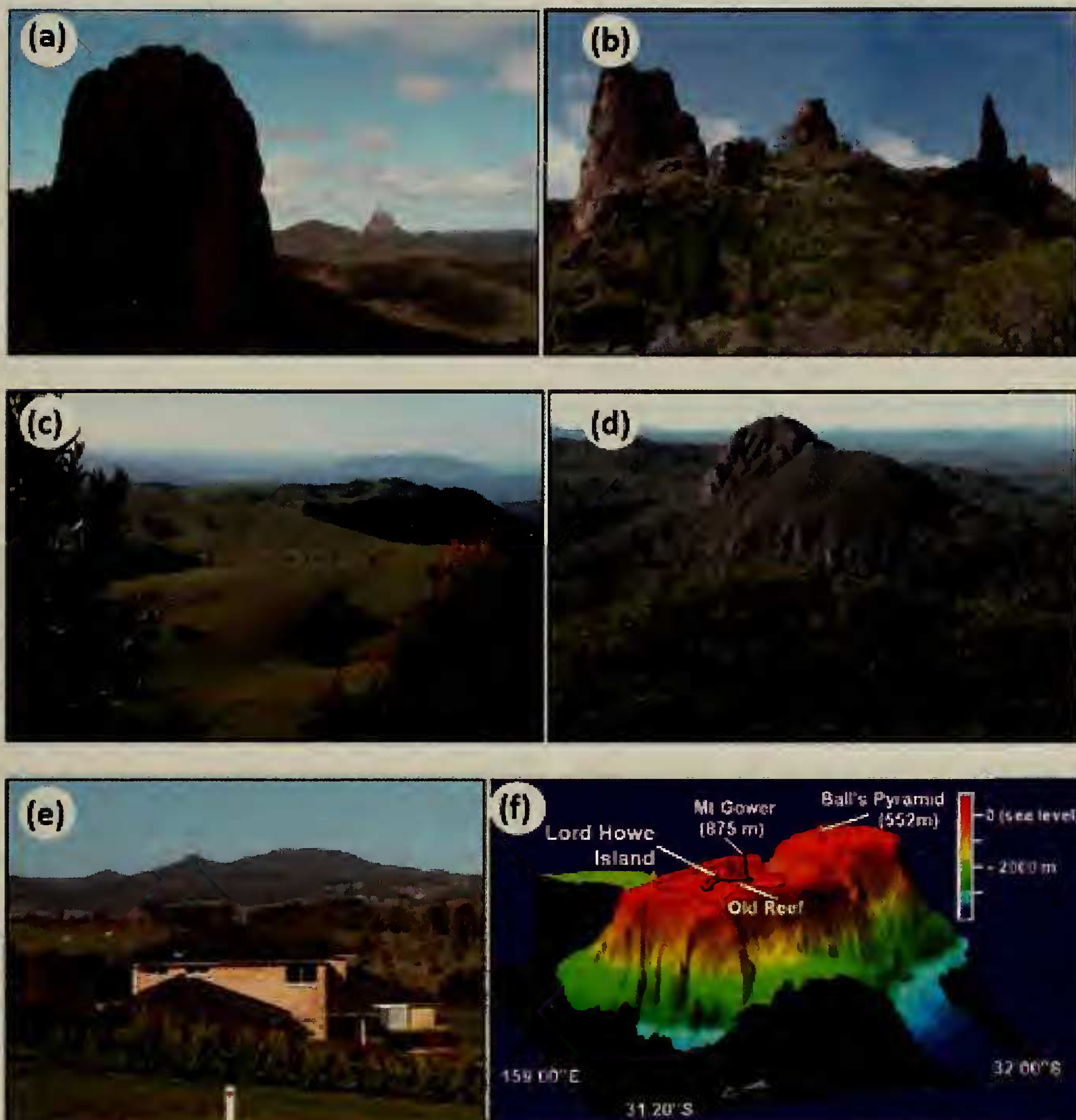

Figure 5. Erosional features developed on younger central volcanoes. (a) View across eroded intrusive core, Warrumbungle Volcano. (b) Silicic plugs and dykes, Warrumbungle Volcano. (c) Basalt Plateau, Comboyne Volcano. (d) Big Nellie silicic plug, Comboyne Volcano. (e) Silicic summit from edge of basalt apron, Canobolas Volcano. Photos: Benjamin Cohen. (f) Submerged basalt pedestal, reef growth and island peaks, Lord Howe Volcano (adapted from Hill et al. 2001).

bird species flourish, including a remarkable range of parrots and many lizard and snake species dwell among the rocky exposures.

Comboyne Volcano

This volcano (25 x 35 km) is preserved as a dissected plateau beside the main escarpment, centred near the town of Comboyne (Pain and Ollier 1986). Lower basalt flows are capped by silicic flows between c. 400–700 m asl (Fig. 5 c) and scattered silicic intrusives up to 865 m asl (Fig. 5 d) mostly rise through basement exposures (Knutson 1989). To the southeast, lower basalts and a trachyte outcrop at Mount Juhle and further south silicic intrusives continue as far as Wingham down to c. 10 m asl. Silicic units give Ar-Ar dates from 16.5–18.1 mya (Knessel et al. 2008; F. L. Sutherland, I. T. Graham and H. Zwingmann, unpublished data). Silicic peaks at Mount Coxcomb, Mount Goonuk and at Big Nellie, Flat Nellie and Little Nellie feature at Mount Coxcomb NR, Mount Goonuk NR and Killabakh NR and Corrabakh NP (Evans 2001; Westerman 2004), while basalt flows on Camboyne plateau feature in Boorganna NR. The name Comboyne is derived from an aboriginal word for kangaroo.

The plateau-escarpment connection in this volcanic area provides complex habitats. Corrabakh NP is an important area for many rare, threatened and endangered plant species, with some lying at their southern limits, while the plugs at Big Nellie support eucalypt species at unusually low altitudes. Endangered animals include the bush curlew and the giant barred frog.

Canobolas Volcano

This small shield (30 x 50 km) largely retains a compact cone-like profile (Fig. 5 e), rising from c.900 m to a summit at 1395 m asl. Its geomorphic features, ranges in basaltic and silicic rocks and the soils are described by Pogson and Watkins (1998) and Chan (2003). Some Ar-Ar dating suggests construction from 13.3 to 11.5 mya (Cohen et al. 2008). The main edifice lies within Mount Canobolas SCA. The mountain name comes from the Wirudyri aboriginal words 'Gaahna Bulla' meaning two shoulders, which describes the two main peaks of 'Old Man Canobolas' and 'Young Man Canobolas' in the eroded volcano.

Mount Canobolas SCA, located on an isolated rocky 'island' rising from surrounding plains, forms an important moist micro-climate habitat for plant and animal communities. Its outcrops host a variety of mosses and lichens, including endangered lichen communities. The mountain supports snow gum sub-alpine woodlands, including the threatened endemic *Eucalyptus canobolas*.

Lord Howe Volcano

This oceanic volcanic island, with its satellite Balls Pyramid to the south, falls under NSW jurisdiction and UNESCO World Heritage listing (Hutton 2008; UNESCO 2010). It is described here with the central volcanoes as part of an age-progressive oceanic volcanic chain (Mortimer et al. 2010), which has a similar, but not contemporaneous, origin to those along the eastern Australian seaboard (Duncan and McDougall 1989). It is largely basaltic, without observed silicic components, but most of the structure (Fig. 5f) forms a large, hidden submarine pedestal (30 x 80 km). Only part of its former caldera lava-filling now stands above sea level and reaches up to 875 asl (Thompson et al. 1987; Hill et al. 2001). The K-Ar dating suggests a 6.5–7 mya construction age.

The Lord Howe Island State MP, gazetted in 1999, and the Lord Howe Island (Commonwealth Waters) NP, proclaimed in 2000, cover several specific areas on the bevelled submarine platform on the volcano, which are presently under revised management arrangements (www.mpa.nsw.gov.au; www.environment.gov.au). Studies of the offshore marine platform recently revealed that a much larger fringing coral reef existed around the Island prior to growth of the present reef since 7 kya (Woodroffe et al. 2010).

BASALT LAVA FIELD COMPONENT

Significant basalt-only lava fields extend throughout eastern NSW and their soil types and vegetation show differences related to their regional climates (Jenkins and Morand 2002). The basalts range from alkaline (nephelinites, basanites, alkali basalts, hawaiites, mugearites) into subalkaline (transitional basalts, olivine tholeiites, quartz tholeiites) types (O'Reilly and Zhang 1995; Vickery et al. 2007). The central New England and Walcha fields occupy significant areas of the New England Tablelands. Voluminous basalts form the Liverpool Range between the Tablelands and the Hunter Valley, while the Barrington province extends through the Mount Royal Range into the Barrington Tops plateau. Lavas in the central New England field (70 x 240 km) reach elevations over 1370 m asl, show a wide age range (14–40 mya) and include alkaline and subalkaline basalts (Vickery et al. 2007). The exposures are largely devoted to pastoral and gem mining pursuits (sapphires and zircon) and only support limited nature reserves (Glen Innes-Guyra basalts, www.environment.gov.au).

A feature of some basalt fields is their growth by repeated eruptions over an extended period, e.g. for over 55 my in the Barrington province. This aspect of 'hydra-head' growth through progressive cut back of earlier volcanoes and subsequent replacement during the eruptive history is illustrated for the North Barrington-Barrington Tops fields in Fig. 6.

Walcha field

Basalts extend over 60 x 60 km and descend from 1200 m to 950 m asl. Alkaline to subalkaline types range in age from 35–73 mya and include gem-bearing types (Sutherland and Barron 2003; Sutherland et al. 2005; Gibson 2007; F.L. Sutherland, I.T. Graham and H. Zwingmann, unpublished data). Deep incision of flows feature in Mummel Gulf NP and basalts extend through Riamukka SF to the west and Einfield SF to the east. Further basalt areas lie

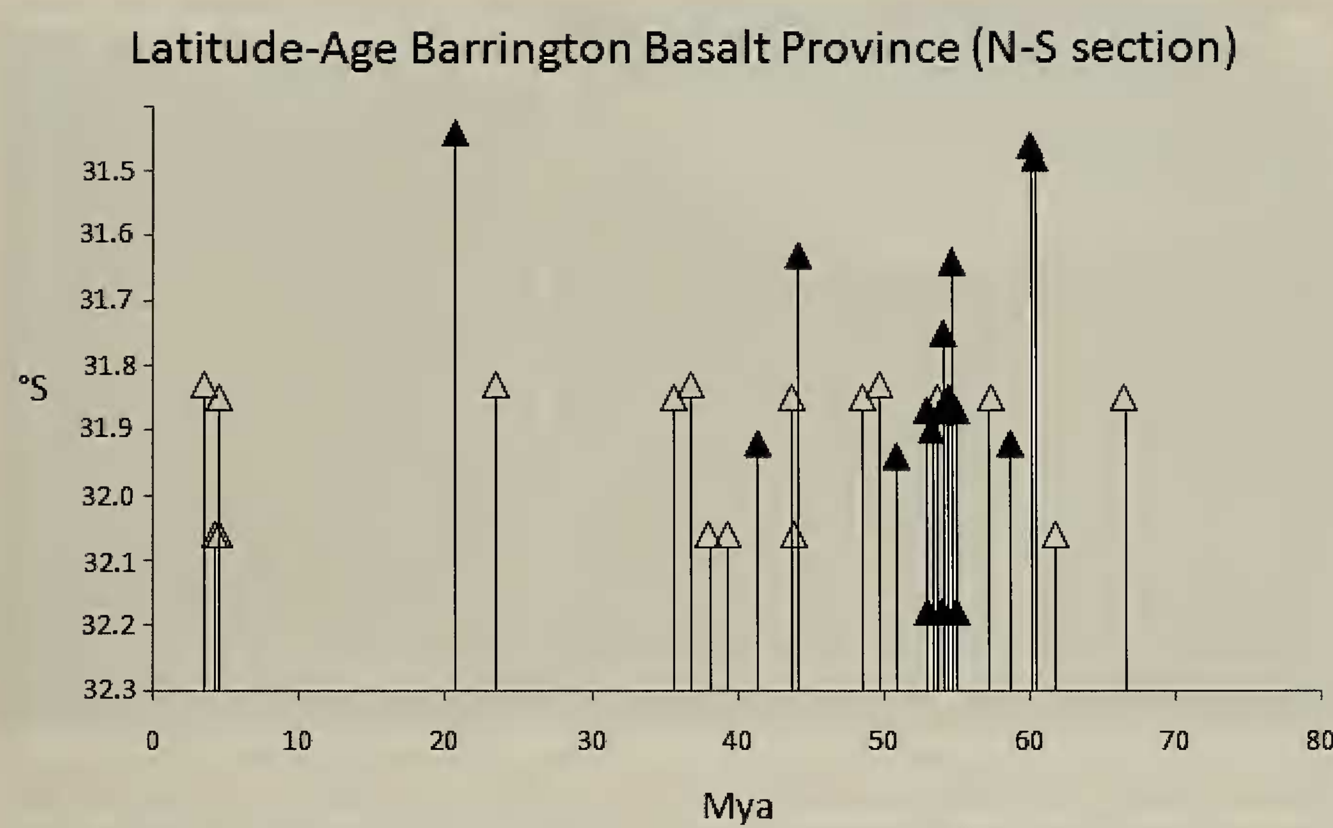

Figure 6. Latitude (°S)–Age (mya) diagram for eruptive centres across a N-S section , Barrington basalt province, including Mount Royal Range and Barrington Tops Plateau, with lava-dominant volcanic centres (K-Ar, solid triangles) and zircon-ages (FT, open triangles). Age data come from Sutherland and Fanning (2001), Roberts et al. (2004), Sutherland et al. (2005a) and Gibson (2007).

in Nowendoc NP and Ngulin NR. Mummel Gulf NP protects extensive old growth forests, which support a large range of bird species, forest bats and small mammals, such as the brown antechinus.

Liverpool Range field

This large basalt field (50 x 120 km) lies between 650–1400 m asl and its dating and petrology is summarised in Schön (1989). Older more alkaline lavas occur to the east (32–35mya) and younger alkaline to transitional subalkaline lavas (38–40mya) form the western sequence. Wallabadah Rock is an unusual isolated rhyolite plug chemically similar to, but older than, the rhyolites in other central volcanoes, as it gave a 46 mya age (Gibson 2007).

Coolah Tops NP extends across the main erosional crest of the western basalts; it forms an isolated basalt plateau that preserves tall open forest communities that differ from the forests on other basalt reserves in the district (Binns 1996). Towarri NP on the southern basalt slopes overlaps three biogeographical regions, the NSW northern Tablelands, Briglow black soil country and Sydney Basin sandstone exposures; these habitats along with Hunter Valley acting as a conduit for migrating species hold considerable biodiversity (Hill et al. 2001). Ben Hall Gap NP lies on the eastern basalt plateau across a drainage divide and has outstanding tall old growth eucalypt forests developed on the thick, nutrient-rich basalt soil (Mitchell 1990); it marks the northern limit of the southern cold temperature rain forests and overlaps the eastern and western distributions of many bird species.

Barrington field

These basalts extend east of the Hunter Valley (Chambers 1995; Sutherland and Graham 2003). The volcanoes show a wide age range (21–61 mya; Gibson 2007), with evidence of limited late activity extending to < 4 mya (Sutherland et al. 2005a) and the basalts are largely alkaline with minor subalkaline types (Sutherland and Fanning 2001). Many Barrington Tops eruptive events carried up gemstones (ruby, sapphire and zircon), which were concentrated in alluvial deposits (Roberts et al. 2004). The main basalt regions lie within the Mount Royal NP, Barrington Tops NP and Barrington Tops SCA in areas which are monitored using vegetation surveys (Zoete 2000). At Barrington Tops, the plateau basalts (Fig. 7 a) reach up to 1576 m asl, and radial drainage has developed

Figure 7. Barrington Tops basalt field, showing erosional features. (a) Plateau surface with drainage headwaters between older 59 mya basalts (left) and younger 50–55 mya basalts (right), Hunter Springs. (b) Dissected plateau scarp, northeastern Barrington Tops Plateau, looking from Moppys Lookout. Photos: F.L. Sutherland.

peripheral escarpments and deep valleys (Fig. 7 b) that cut through the basalts into basement rocks between 600–900 m asl.

Barrington Tops NP and Mount Royal NP include segments of the World Heritage-listed Gondwana Rainforest of Australia for their subtropical rainforests that occupy valleys in the basalt plateaus (UNESCO 2010). The diverse habitats provide refuge for threatened animal species such as the Hastings River mouse.

Mid-NSW basalt fields

Scattered remnants extend through the Sydney-central coast area and westwards into the Oberon and Bathurst areas. Basalt dykes intrude coastal sections between Newcastle and Wollongong and some are Cenozoic, such as those at Era Beach in Royal NP south of Sydney, which gave a 51 mya K-Ar age (Och et al. 2009). Younger alkaline basalts (14–21 mya), such as at Mount Banks, fall within Blue Mountains NP (Alder and Pickett, 1997; Van der Beek et al. 2001) and Mount Yengo NP (Mount Warrenga, Gibson 2007). Older basalts (34–57 mya) extend through Mount Yengo NP, Wollemi NP and Nullo Mountain SF. They rise to 1154 m asl at Tayan Pic, a designated significant geological site, and include Mounts Coricudgy, Pomany, Corriday, Mondilla, Coorangoola and Kerry and Nullo Mountains (Gibson 2007). Mount Yengo formed a significant mythological feature for surrounding aboriginal tribes as a Creator God, Biamie. These basalt peaks and soils influence local habitats within the wide range of eucalypt species developed across the sandstone platforms of the Greater Blue Mountains World Heritage area (UNESCO 2010).

Basalt and dolerite remnants in Abercrombie River NP represent former lavas that extended into headwaters of west-flowing paleodrainage systems, while other basalts entered former Lachlan and Macquarie River courses downstream as far west as the Dubbo-Orange area (Bishop and Brown 1992; Tomkins and Hesse 2004).

Southern NSW fields

The Southern Highlands (100 x 110 km) and Grabben Gullen fields (30 x 40km) southwest of Sydney contain scattered basalt patches with diverse ages (20–60mya; Gibson 2007) and are mostly alkali basalts with confined flow extents (O'Reilly and Zhang 1995). Minor remnants lie within Tarlo NP and rainforest on basalt is preserved in Robertson NR. Further south, alkaline and subalkaline basalts form flows (40–50mya) within the Shoalhaven catchment area and were used to demonstrate the relative antiquity of the plateau surface (Nott et al. 1996). Some flows are found in Morton NP and

Budawang NP. Along south coastal NSW, similar basalt types show younger ages (27–34 mya; Brown 2000), but have induced differing interpretations of their geomorphic relationships with highland development. The northern part of Eurobodalla NP is dominated by basalts, but the largest basalt body forms Mount Durass within the bounds of Greater Murramarang NP (Wright 1996).

To the southwest, basalts in the Snowy field (60 x 80 km) are mostly alkaline types that remain as valley filling ridges and plateaus of Miocene flows (18–24 mya) that range in their elevations from 450 m to summit sources up to 1784 m asl (Sutherland et al. 2002; Sharp 2004). These basalts have engendered considerable discussion on their relationships to the age and uplift history of the surrounding uplands (Young and McDougall 2004). Many of the higher basalts are included in Kosciuszko NP and the Tabletop wilderness area while lower plateau basalts lie within Bago SF. The largest southern field (45 x 110 km) is the Monaro field, where alkaline and some subalkaline sequences (34–58 mya; Gibson 2007) preserve important evidence of early vegetation and climatic records (Taylor et al. 1990; Brown 1994; Roach et al. 1994; Taylor and Roach 2003; Sharp 2004). Although some basalts are located in South East Forests NP and some central-northern reserves (Conartha NR, Myall NR), the bulk of the basaltic soils support grasslands that include a number of preservation areas for endemic species (Garden et al. 2001; Benson 2003).

DISCUSSION

New South Wales is well-endowed with national parks and ancillary reservations, containing over 380 listed sites covering 7% of the State's area (NSW Government websites). Among some sixty national parks, most lie on the eastern side of the state (Explore Australia 2010), where some 30 of them cited in this survey contain exposures of Cenozoic volcanic rocks. This highlights the important role that this unit occupies within the geodiversity on offer in NSW reservations. The most diverse range of rocks and landforms appear in the central volcano shields, where contrasts between basaltic and silicic lithologies lead to more pronounced differences in erosional forms and soil developments. This translates into greater variations in vegetation make up and habitats for fauna. Rainforests tend to develop on nutrient-rich basalt areas while eucalypt sclerophyll stands tend to colonise nutrient-deficient soils on silicic rocks. Nightcap NP, which has the highest annual rainfall in NSW, supports subtropical rainforest on its basalt soils and warm-temperate rainforest on its rhyolite-based soils. The lithological nature and topography in the volcanic areas also dictates land use. Areas with rich basalt soils on flatter, accessible terrains with favourable hydrological characteristics encourage agricultural use (Brodie and Green, 2002), whereas rugged scarps are often too steep for cultivation. Juxtaposed lithological contrasts in the central volcanoes provide scenic appeal for visitors and with their biodiversity factors has led to their prevalent inclusion within parks and reservations.

Systematic geodiversity

The NSW central volcanoes show a general change in their ages (from 25 to 12 mya) and size (from 80 x 100 to 30 x 50 km across) with latitude southwards (28.2 to 33.4°S). This change provides a systematic base to study their geological and habitat variations, related to climate and variable length of erosion and weathering time. This general rule, however, excludes Belmore Volcano. Here, the absence of basalts led to a reduced shield area and a different erosional history and land use. The older northern volcanoes (Main Range-Tweed) provide examples of more extreme erosional relief and habitat ranges than the younger southern Canobolas Volcano, where its remaining profile lacks marked internal topographic disruptions. Habitats are largely limited by basaltic/silicic soil distribution, altitude and hydrological changes from the surrounding plains to the mountain summit.

Two separate central volcano chains formed during their progressive development southwards, giving eastern (Qld-NSW border volcanoes, Belmore, Ebor, Comboyne) and western (Nandewar, Warrumbungle, Canobolas) lines. This brought another systematic erosional factor into play, the intersections of some volcanoes by escarpment retreat towards the east Australian divide during drainage development (Ollier and Pain 2000). The Tweed and Belmore volcanoes grew onto the coastal margin so that the escarpment retreat had intersected their positions by 24–20 mya respectively, but not those of the Main Range and Ebor volcano, which are only now half removed by the escarpment inroads. The Comboyne volcano remains almost connected to the escarpment and the western centres lack the extreme division of habitats caused by escarpment intersections.

Among the basalt fields, systematic differences in habitats can appear where adjoining fields show significant age differences. In southeast NSW, the older Monaro field with more deeply developed soil profiles supports natural grasslands and forests that contrast with less deeply weathered plateau and flow caps that remain in alpine and foothill settings in the Snowy field.

Geodiversity platforms

Variations in volcanic rock types, their ages, landforms and weathering characteristics all feature within this one Cenozoic unit, within the overall geological diversity in NSW. This range in lithology, soil types and dissected features, at different altitudes and geographic locations, both inland and coastal has developed a multitude of diverse habitats. This linkage provides an important platform for promoting the role of geodiversity in the environment. It provides opportunities for multidisciplinary scientific studies, geo-heritage assessments, geo-education and geo-tourism. Examples of multidisciplinary studies that use NSW Cenozoic volcanic components include landform ecological analysis (Mitchell 2003), hydro-geomorphic comparisons (Gibson 2008), aboriginal stone tool analysis (Bowdler 2005; Corkhill 2005), and archaeological appraisals (McIntyre-Tamwoy 2008). Geo-heritage listings range from individual rocks (Nimbin rhyolite, Osborne et al. 1998) to clusters of sites (basalt ridges of the Liverpool and Mount Royal Ranges, Schön 1984) and also large-scale features (Warrumbungle Volcano; Australian Heritage Commission 2010).

Geo-education utilises the NSW volcanic features in varied ways, including inclusion in explanatory books and guides for recreational visitors (Blanch and Kean 1995; Alder and Pickett 1997; Gold and Prineas 1997; Ferret 2005; Whitehead 2008), more specialised visitors (Duggan and Knutson 1993; Sutherland and Graham 2003) or even extending to fanciful stories for children's (Hutchison 2010). Educational slide sets that feature Australian volcanoes include NSW examples (Lewis et al. 1998), while documentary video films feature NSW volcanic backgrounds, particularly the Tweed Volcano, in integrations of landforms and ecology (Sutherland 2008; Warth 2009). An interactive website for school students on Australian volcanoes is maintained by Uni Serve-Science (2001). Geo-tourism is catered for by a range of web sites which list NSW volcanic attractions (www.bigvolcano.com.au) and includes special self-operating tours (Bob and Nancy's Geo-tours 2010).

Although many avenues exist to explore the Cenozoic volcanic features in NSW, there is further scope for promoting their importance both for assisting in their preservation and for exploiting their explanatory role in illustrating geological processes. The systematic differences, within and between the large central volcanoes and basalt fields, provide considerable capacity for developing overarching themes that link their individual features into a grander picture. For example, although each central volcano has its own geological history as a group they can be linked to Australia's plate motion movement away from Antarctica and the concepts of global 'hot spot' volcanic traces elsewhere. Likewise, individual basalt fields can be related to their place within the long evolution of volcanic activity along the Tasman margin, to concepts of landscape inversion or to how they preserve records of former biodiversity during Australia's natural history evolution. Many of the volcanic fields can be linked into preservation of 'Gondwana' rainforest reserves (United Nations Environment Program-Wo 2008).

Unfinished story

The NSW Cenozoic volcanic record developed through to its present landscapes over a 100 my period and volcanism still remains dormant in far northern Queensland, western Victoria and SE South Australia (Johnson 2004). The NSW landforms discussed here only acquired minor, mostly explosive additions in the last 10 my, while erosion further dissected the lavas. Nevertheless, the rocks remain as valuable assets to further decipher their genesis while still generating scientific debate as to the exact causes. Increasing use of more precise dating, high-quality geochemical and isotopic analysis and well-controlled geodynamic modelling continues to furnish new insights into the origin of the volcanism (Vasconcelos et al. 2008; Di Caprio et al. 2009).

The onset of extensive basaltic lava field activity, as found in eastern Australia, is correlated by some workers with global mantle warming effects without other extraneous causes (Coltice et al. 2007), whereas other workers look to additional factors such as buoyant rise of hot mantle wedges when subduction ceased as important mechanisms (Rey and Muller 2010). For progressive central volcano activity on moving plates, fixed deep mantle thermal plumes are commonly invoked, but such activity can also be explained by other means (Reitsma and Allen 2003; Finn et al. 2005). For the eastern Australian central volcanoes different interpretations of their tracks include plumes deflected by mantle processes (Sutherland 2003), plumes deflected by thick subcontinental roots (Manglik and Christensen 2006) or plumes that directly record changes in Australian plate motion (Knessel et al. 2008), but resolution of these views needs further scientific testing. Thus, the intrinsic geodiversity revealed among the NSW Cenozoic volcanic areas continues to be updated and refreshed for presentation to scientific, recreational and geo-tourist audiences. This volcanic heritage can be continually worked into new concepts, such as the new approaches to geodiversity and ecosystem services (Gordon and Brown 2010).

CONCLUSIONS

Cenozoic volcanic remnants form significant contributions to National Parks and reserves in eastern NSW. The large central volcano sites decrease in age and size from the northern border to central NSW, causing corresponding variations in landforms and habitats. The basalt lava fields show a greater age range, lack the silicic attributes within central volcanoes, and develop wider latitudinal and altitudinal habitats. The geodiversity just within this volcanic unit provides exceptional opportunities to study detailed geological, biological and human interactions.

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